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Energy-Efficient Motors

2.1 STANDARD MOTOR EFFICIENCY

During the period from 1960 to 1975, electric motors, particularly those in the 1- to 250-hp range, were designed for minimum first cost. The amount of active material, i.e., lamination steel, copper or aluminum or magnet wire, and rotor aluminum, was selected as the minimum levels required to meet the performance requirements of the motor. Efficiency was maintained at levels high enough to meet the temperature rise requirements of the particular motor. As a consequence, depending on the type of enclosure and ventilation system, a wide range in efficiencies exists for standard NEMA design B polyphase motors. [Table 2.1](#) is an indication of the range of the nominal electric motor efficiencies at rated horsepower. These data are also presented in [Fig. 2.1](#). The data are based on information published by the major electric motor manufacturers. However, the meaning or interpretation of data published prior to the NEMA adoption of the definition of nominal efficiency is not always clear. In 1977, NEMA recommended a procedure for marking

TABLE 2.1 Full-Load Efficiencies of NEMA Design B Standard Three-Phase Induction Motors

hp	Nominal efficiency range	Average nominal efficiency
1	68–78	73
1.5	68–80	75
2	72–81	77
3	74–83	80
5	78–85	82
7.5	80–87	84
10	81–88	85
15	83–89	86
20	84–89	87.5
25	85–90	88
30	86–90.5	88.5
40	87–91.5	89.5
50	88–92	90
60	88.5–92	90.5
75	89.5–92.5	91
100	90–93	91.5
125	90.5–93	92
150	91–93.5	92.5
200	91.5–94	93
250	91.5–94.5	93.5

the three-phase motors with a NEMA nominal efficiency. This efficiency represents the average efficiency for a large population of motors of the same design. In addition, a minimum efficiency was established for each level of nominal efficiency.

The minimum efficiency is the lowest level of efficiency to be expected when a motor is marked with the nominal efficiency in accordance with the NEMA standard. This method of identifying the motor efficiency takes into account variations in materials, manufacturing processes, and test results in motor-to-motor efficiency variations for a given motor design. The nominal efficiency represents a value that should be used to compute the energy

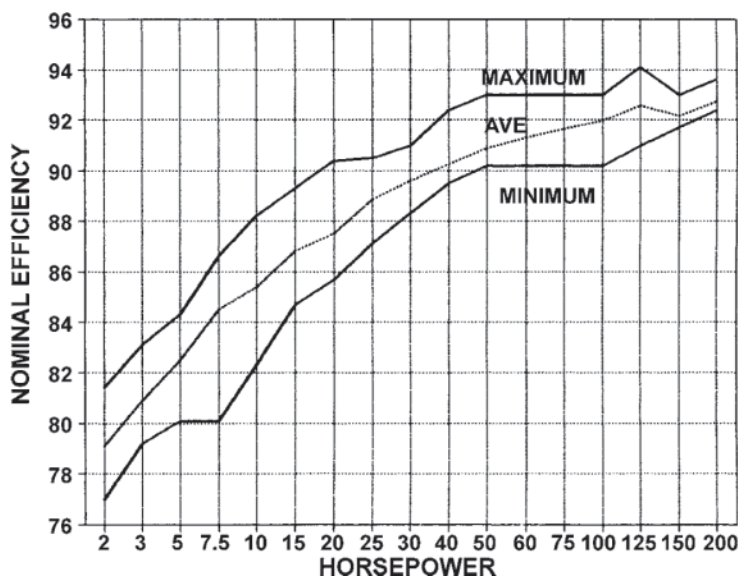


FIGURE 2.1 Nominal efficiency range of standard open NEMA design B 1800-rpm polyphase induction motors.

consumption of a motor or group of motors. Table 2.1 shows a wide range in efficiency for individual motors and, consequently, a range in the electric motor losses and electric power input. For example, a standard 10-hp electric motor may have an efficiency range of 81–88%.

At 81% efficiency,

$$\text{Input electric power} = \frac{10 \times 746}{0.81} = 9210 \text{ W}$$

$$\text{Motor losses} = 9210 - 7460 = 1750 \text{ W}$$

At 88% efficiency,

$$\text{Input electric power} = \frac{10 \times 746}{0.88} = 8477 \text{ W}$$

$$\text{Motor losses} = 8477 - 7460 = 1017 \text{ W}$$

Therefore, for the same output the input can range from 8477 to 9210 W, or an increase in energy consumption and power costs of 8%, to operate the less efficient motor.

2.2 WHY MORE EFFICIENT MOTORS?

The escalation in the cost of electric power that began in 1972 made it increasingly expensive to use inefficient electric motors. From 1972 through 1979, electric power rates increased at an average annual rate of 11.5%/yr. From 1979 to the present, the electric power rates have continued to increase at an average annual rate of 6%/yr. The annual electric power cost to operate a 10-hp motor 4000 hr/yr increased from \$850 in 1972 to \$1950 in 1980 and to over \$2500 by 1989. By 1974, electric motor manufacturers were looking for methods to improve three-phase induction motor efficiencies to values above those shown for standard NEMA design B motors in [Table 2.1](#).

2.3 WHAT IS EFFICIENCY?

Electric motor efficiency is the measure of the ability of an electric motor to convert electrical energy to mechanical energy; i.e., kilowatts of electric power are supplied to the motor at its electrical terminals, and the horsepower of mechanical energy is taken out of the motor at the rotating shaft. Therefore, the only power absorbed by the electric motor is the losses incurred in making the conversion from electrical to mechanical energy. Thus, the motor efficiency can be expressed as

$$\text{Efficiency} = \frac{\text{mechanical energy out}}{\text{electrical energy in}} \times 100\%$$

but

$$\begin{aligned} \text{Mechanical energy out} &= \text{electrical energy in} \\ &\quad - \text{motor losses} \end{aligned}$$

or

$$\begin{aligned} \text{Electrical energy in} &= \text{mechanical energy out} \\ &\quad + \text{motor losses} \end{aligned}$$

Therefore, to reduce the electric power consumption for a given mechanical energy out, the motor losses must be reduced and the electric motor efficiency increased.

To accomplish this, it is necessary to understand the types of losses that occur in an electric motor. These losses consist of the following.

2.3.1 Power Losses

The power losses (I^2R in the motor windings) consist of two losses: the stator power losses I^2R and the rotor power losses I^2R . The stator power loss is a function of the current flowing in the stator winding and the stator winding resistance—hence the term I^2R loss:

$$\text{Stator current } I_1 = \frac{\text{input watts}}{\text{voltage} \times \sqrt{3} \text{ PF}}$$

When improving the motor performance, it is important to recognize the interdependent relationship of the efficiency and the power factor. Rewrite the preceding equation and solve for the power factor:

$$\text{PF} = \frac{\text{output hp} \times 746}{\text{voltage} \times \sqrt{3} \text{ efficiency} \times I_1}$$

Therefore, if the efficiency is increased, the power factor will tend to decrease. For the power factor to remain constant, the stator current I_1 must decrease in proportion to the increase in efficiency. To increase the power factor, the stator current must be decreased more than the efficiency is increased. From a design standpoint, this is difficult to accomplish and still maintain other performance requirements such as breakdown torque. However,

$$\text{Input watts} = \frac{\text{output hp} \times 746}{\text{efficiency}}$$

or

$$I_1 = \frac{\text{output hp} \times 746}{\text{voltage} \times \sqrt{3} \text{ PF} \times \text{efficiency}}$$

Therefore, the stator losses are inversely proportional to the square of the efficiency and the power factor. In addition, the stator loss is a function of the stator winding resistance. For a given configuration, the winding resistance R is inversely proportional to the pounds of

magnet wire or conductors in the stator winding. The more conductor material in the stator winding, the lower the losses.

The rotor power loss is generally expressed as the slip loss:

$$\text{Rotor loss} = \frac{(\text{hp output} \times 746 + \text{FW})S}{1 - S}$$

$$S = \frac{N_s - N}{N_s} = \text{slip}$$

where

N = output speed, rpm

N_s = synchronous speed, rpm

FW = friction and windage loss

The rotor slip can be reduced by increasing the amount of conductor material in the rotor or increasing the total flux across the air gap into the rotor. The extent of these changes is limited by the minimum starting (or locked-rotor) torque required, the maximum locked-rotor current, and the minimum power factor required.

2.3.2 Magnetic Core Losses

Magnetic core losses consist of the eddy current and hysteresis losses, including the surface losses, in the magnetic structure of the motor. A number of factors influence these losses:

1. The flux density in the magnetic structure is a major factor in determining these magnetic losses. The core loss can be decreased by increasing the length of the magnetic structure and, as a consequence, decreasing the flux density in the core. This will decrease the magnetic loss per unit of weight but, since the total weight will increase, the improvement in losses will not be proportional to the unit loss reduction. The decrease in magnetic loading in the motor also decreases the magnetizing current and thus influences the power factor.
2. The magnetic core loss can also be reduced by using thinner laminations in the magnetic structure. Typically, many

standard motors use 24-gauge (0.025-in. thick) laminations. By using thinner laminations, such as 26-gauge (0.0185-in. thick) or 29-gauge (0.014-in. thick), the magnetic core loss can be reduced. The reduction in the magnetic core loss by the use of thinner laminations ranges from 10 to 25%, depending on the method of processing the lamination steel and the method of assembling the magnetic core.

3. There has been considerable progress made by the steel companies to obtain lower magnetic losses in both silicon and cold-rolled (low-silicon) grades of electrical steel. The magnetic core loss (Epstein loss) can be reduced by using silicon grades of electrical steel or the improved grades of cold-rolled electrical steel. The type of steel used by the motor manufacturer depends on his process capability. The cold-rolled electrical steel requires a proper anneal after punching to develop its electrical properties, whereas the silicon grades of electrical steel are available as fully processed material. [Tables 2.2a](#) and [2.2b](#) illustrate some of the silicon and cold-rolled electrical steels available and the influence of grade and thickness on the Epstein loss and permeability.

However, because of variables in the processing of the lamination steel into finished motor cores, the reduction in core loss in watts per pound equivalent to the Epstein data on flat strips of the lamination steel is seldom achieved. Magnetic core loss reductions on the order of 15–40% can be achieved by the use of thinner-gauge silicon-grade electrical steels. A disadvantage of the higher-silicon lamination steel is that, at high inductions, the permeability may be lower, thus increasing the magnetizing current required. This will tend to decrease the motor power factor.

2.3.3 Friction and Windage Losses

Friction and windage losses are caused by the friction in the bearings of the motor and the windage loss of the ventilation fan and other rotating elements of the motor. The friction losses in the bearings

TABLE 2.2a Typical 50/50 as Sheared Epstein Data for Silicon-Grade Electrical Steel

Electrical steel grade	Standard gage	Nominal thickness, in.	Maximum epstein loss at 15 kg, 60 Hz	Typical permeability at 15 kg, 60 Hz
M-47	24	0.025	3.60	1800
	26	0.0185	3.05	1800
M-45	24	0.025	3.20	1700
	26	0.0185	2.80	1700
M-43	24	0.025	2.70	1500
	26	0.0185	2.30	1500
	29	0.014	2.00	1500
M-36	26	0.0185	2.05	1400
	29	0.014	1.90	1400
M-27	29	0.014	1.80	1200

Note: The Epstein core loss is for fully processed steel; lower losses can be attained with semiprocessed steel and a quality anneal.

Source: Courtesy Armco Advanced Materials Co., Butler, PA.

are a function of bearing size, speed, type of bearing, load, and lubrication used. This loss is relatively fixed for a given design and, since it is a small percentage of the total motor losses, design changes to reduce this loss do not significantly affect the motor efficiency. Most of the windage losses are associated with the ventilation fans and the amount of ventilation required to remove the heat generated by other losses in the motor, such as the winding power losses I^2R , magnetic core loss, and stray load loss. As the heat-producing losses are reduced, it is possible to reduce the ventilation required to remove those losses, and thus the windage loss can be reduced. This applies primarily to totally enclosed fan-cooled motors with external ventilation fans. One of the important by-products of decreasing the windage loss is a lower noise level created by the motor.

TABLE 2.2b Typical Epstein Data Inland Steel Nonsilicon Cold-Rolled Electrical Steel

Inland type	Thickness, in.	Epstein loss, W/lb at 15 kg	Permeability at 15 kg (min.)
Rephosphorized	0.029	4.6	2000
	0.025	3.85	2000
	0.022	3.5	2000
Interlocking	0.029	4.2	2000
	0.025	3.75	2000
	0.022	3.2	2000
2.5/2000	0.025	3.3	2000
	0.022	2.9	2000
	0.018	2.5	2000
2.25/2000	0.025	3.1	2000
	0.022	2.7	2000
	0.018	2.3	2000
2/2000	0.022	2.3	2000
	0.018	2.0	2000

Note: The Epstein values are typical for semiprocessed steel annealed after punching.

Source: Courtesy Inland Steel Flat Products Co., Chicago, IL.

2.3.4 Stray Load Losses

Stray load losses are residual losses in the motor that are difficult to determine by direct measurement or calculation. These losses are load related and are generally assumed to vary as the square of the output torque. The nature of this loss is very complex. It is a function of many of the elements of the design and the processing of the motor. Some of the elements that influence this loss are the stator winding design, the ratio of air gap length to rotor slot openings, the ratio of the number of rotor slots to stator slots, the air gap flux density, the condition of the stator air gap surface, the condition of the rotor air gap surface, and the bonding or welding of the rotor conductor bars to rotor lamination. By careful design, some of the elements that contribute to the stray loss can be minimized. Those

stray losses that relate to processing, such as surface conditions, can be minimized by careful manufacturing process control. Because of the large number of variables that contribute to the stray loss, it is the most difficult loss in the motor to control.

2.3.5 Summary of Loss Distribution

Within a limited range, the various motor losses discussed are independent of each other. However, in trying to make major improvements in efficiency, one finds that the various losses are very dependent. The final motor design is a balance among several losses to obtain a high efficiency and still meet other performance criteria, including locked-rotor torque, locked-rotor amperes, breakdown torque, and the power factor.

The distribution of electric motor losses at the rated load is shown in [Table 2.3](#) for several horsepower ratings. It is important for the motor designer to understand this loss distribution in order to make design changes to improve motor efficiency. In a very general sense, the average loss distribution for standard NEMA design B motors can be summarized as follows:

Motor component loss	Total loss, %
Stator power loss I^2R	37
Rotor power loss I_2^2R	18
Magnetic core loss	20
Friction and windage	9
Stray load loss	16

This loss distribution indicates the significance of design changes to increase the electric motor efficiency. However, as the motor efficiency and the horsepower increase, the level of difficulty in

TABLE 2.3 Typical Loss Distribution of Standard NEMA Design B Drip-Proof Motors

Loss distribution	1 hp			5 hp		
	Watts	% Loss	PU loss	Watts	% Loss	PU loss
Stator power loss $I_1^2 R$	120	43	0.16	305	40	0.08
Rotor power loss $I_2^2 R$	35	13	0.05	150	20	0.04
Magnetic core loss	76	28	0.10	225	29	0.06
Friction and windage loss	24	9	0.03	30	4	0.01
Stray load loss	19	7	0.03	51	7	0.01
Total losses	274	100	0.37	761	100	0.20
Output, W	746			3730		
Input, W	1020			4491		
Efficiency, %	73			83		

Notes: Polyphase four-pole motor, 1750 rpm. % loss = percent of total losses. PU loss = loss/(hp $\times$ 746).

improving the electric motor efficiency increases. Consider the stator and rotor power losses only. To improve the motor full-load efficiency, one efficiency point requires an increasing reduction in these power losses as the motor efficiency increases:

hp	Original efficiency, %	Increased efficiency, %	Decrease in power losses required, %
1	73.0	74.0	8
5	83.0	84.0	11
25	89.0	90.0	16
50	90.5	91.5	19
100	91.5	92.5	28
200	93.0	94.0	38

These loss reductions can be achieved by increasing the amount of material, i.e., magnet wire in the stator winding and aluminum

25 hp			50 hp			100 hp			200 hp		
Watts	% Loss	PU loss	Watts	% Loss	PU loss	Watts	% Loss	PU loss	Watts	% Loss	PU loss
953	42	0.05	1,540	38	0.04	1,955	28	0.026	3,425	30	0.023
479	21	0.03	860	22	0.02	1,177	18	0.016	1,850	16	0.012
351	15	0.02	765	20	0.02	906	13	0.012	1,650	15	0.011
168	7	0.01	300	8	0.01	992	14	0.013	1,072	10	0.007
345	15	0.02	452	12	0.01	1,900	27	0.025	3,235	29	0.022
2,296	100	0.13	3,917	100	0.10	6,930	100	0.092	11,232	100	0.075
18,560			37,300			74,600			149,200		
20,946			41,217			81,530			160,432		
89			90.5			91.5			93.0		

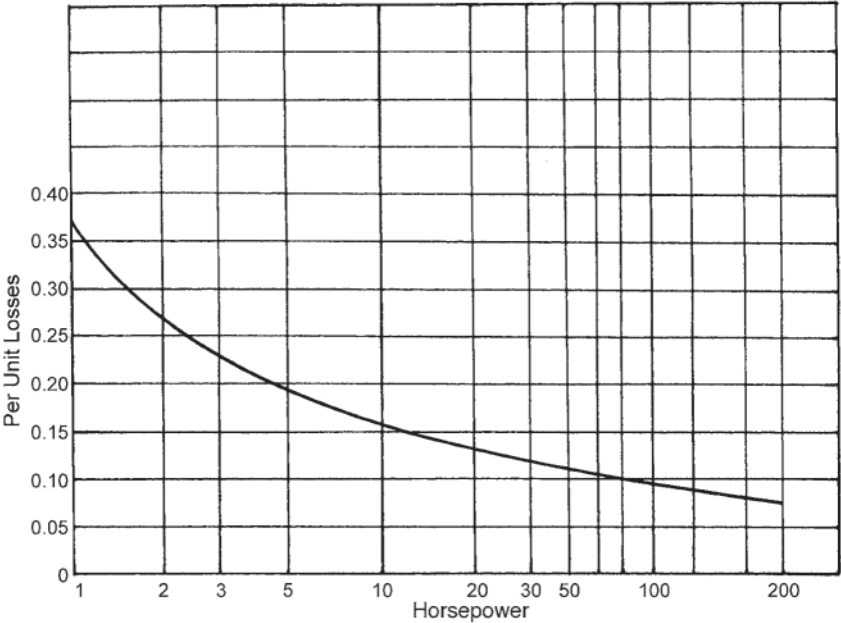


FIGURE 2.2 Per unit losses for standard design B four-pole motors.

conductors in the rotor or squirrel-cage winding. However, a loss deduction of only 5–15% can be achieved in these power losses without making other design modifications. These modifications can include a new lamination design to increase the amount of magnet wire and aluminum rotor conductors that can be used, combined with the use of lower-loss electrical-grade lamination steel in the magnetic structure and the use of a longer magnetic structure. The level of difficulty and, consequently, the cost of improving the electric motor efficiency increases as the horsepower rating increases. This is illustrated in Fig. 2.2, which shows the decrease in per unit losses as the horsepower rating increases, thus requiring a larger per unit loss reduction at the higher horsepower ratings for the same efficiency improvement.

2.4 WHAT IS AN ENERGY-EFFICIENT MOTOR?

Until recently, there was no single definition of an energy-efficient motor. Similarly, there were no efficiency standards for standard NEMA design B polyphase induction motors. As discussed earlier, standard motors were designed with efficiencies high enough to achieve the allowable temperature rise for the rating. Therefore, for a given horsepower rating, there is a considerable variation in efficiency. This is illustrated in Fig. 2.1 for the horsepower range of 1–200 hp.

In 1974, one electric motor manufacturer examined the trend of increasing energy costs and the costs of improving electric motor efficiencies. The cost/benefit ratio at that time justified the development of a line of energy-efficient motors with losses approximately 25% lower than the average NEMA design B motors. This has resulted in a continuing industry effort to decrease the watt losses of induction motors. Figure 2.3 shows a comparison between the full-load watt losses for standard four-pole, 1800-rpm NEMA design B induction motors, the first-generation energy-efficient motors with a 25% reduction in watt losses, and the current energy-efficient motors. The watt loss reduction for the current energy-efficient four-pole, 1800-rpm motors ranges from 25 to 43%, with

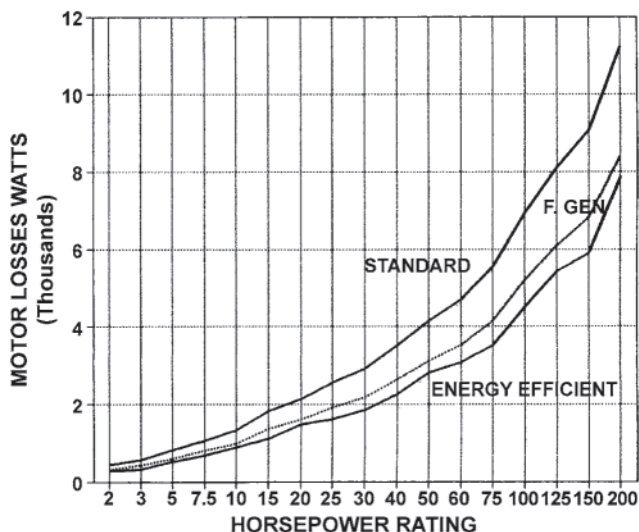


FIGURE 2.3 Full-load losses, standard NEMA Design B 1800-rpm motors versus first-generation energy-efficient motors (25% loss reduction) and current energy-efficient motors.

an average watt loss reduction of 35%. [Figures 2.4a](#) and [2.4b](#) illustrate the nominal efficiencies of the current energy-efficient (E.E.) motors, the first-generation energy-efficient motors (25% loss reduction), and current standard NEMA design B four-pole, 1800-rpm motors.

Subsequent to the development of this first line of energy-efficient motors, all major electric motor manufacturers have followed suit. Since, as previously discussed, there was no standard for the efficiency of motors, the energy-efficient motors of the various manufacturers can generally be identified by their trade names. In addition, these

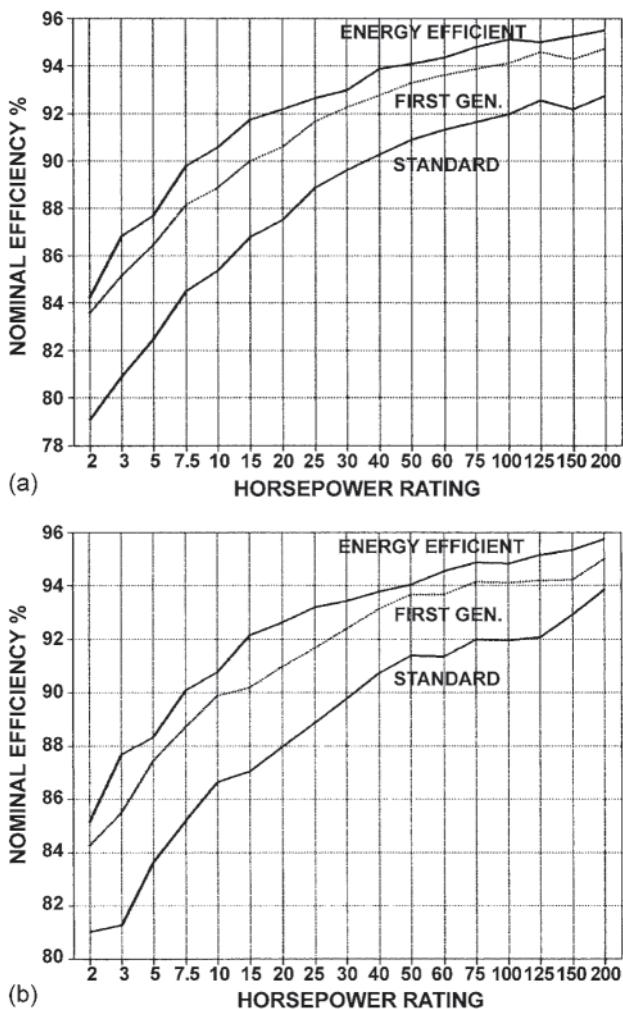


FIGURE 2.4 (a) Nominal full-load efficiency comparison 1800-rpm open induction motors. (b) Nominal full-load efficiency comparison 1800-rpm TEFC induction motors.

products are supported by appropriate published data. Following are examples of these trade names and their manufacturers:

E-Plus®, E + III®	Magnetek
Energy Saver™	General Electric
XE Energy Efficient	Reliance Electric Co.
Super E	Baldor Electric Co.
Spartan High Efficiency	Magnetek/Louis Allis
Corro-Duty Premium Efficiency	U.S. Electrical Motors
Premium Efficiency	Division of Emerson Electric Co. Seimens
Premium Efficiency	Toshiba/Houston Intl.

A survey of the published data available from the manufacturers of energy-efficient motors is summarized in [Table 2.4](#) and [Fig. 2.5](#). These data show the nominal average efficiency as well as the range of nominal efficiencies expected. The efficiencies are shown as nominal efficiencies as defined in NEMA Standards Publication MG1. When these efficiency data are compared to the standard motor efficiency data shown in [Fig. 2.1](#), the range in efficiency for a given horsepower is considerably less; in other words, energy-efficient motors tend to be more uniform than standard motors.

When the average nominal efficiency for industry energy-efficient motors shown in [Tables 2.4a](#) and [2.4b](#) is compared to the data shown in [Fig. 2.4](#) for standard motors, the industry average is consistently higher. When the average efficiency for standard motors in [Fig. 2.1](#) is compared to the average efficiency for current energy-efficient motors in [Figs. 2.5a](#) and [2.5b](#) the average loss reduction is 35%, thus indicating a continuing trend to higher-efficiency motors. These improvements in efficiency, or loss reductions, are generally achieved by increasing the amount of active material used in the motors and by the use of lower-loss magnetic steel. [Figure 2.6](#) shows this comparison of a standard motor and an energy-efficient motor for a particular horsepower rating. In addition to increasing the motor efficiency, there are other user benefits in the application of energy-efficient motors, which will be discussed in more detail in

TABLE 2.4a Full-Load Nominal Efficiencies of Three-Phase Four-Pole Energy-Efficient Open Motors^a

hp	Nominal efficiency range		Average nominal efficiency
	Min.	Max.	
1	82.5	85.5	83.5
2	82.5	86.0	84.3
3	82.5	89.5	87.0
5	85.5	89.5	87.9
7.5	87.5	91.7	90.0
10	89.5	91.7	90.6
15	90.2	93.0	91.6
20	90.2	93.6	92.1
25	91.0	94.1	92.6
30	91.7	94.1	93.1
40	93.6	94.5	93.9
50	93.6	94.5	94.1
60	93.6	95.4	94.4
75	94.1	95.4	94.8
100	94.1	96.2	95.1
125	94.1	95.4	95.1
150	94.5	96.2	95.3
200	95.0	96.2	95.5

^a Based on available published data.

Chapter 5. This trend will probably continue as the cost of power and the demand for higher-efficiency motors continue to increase. **Figure 2.7** shows the trend in the loss reduction and efficiency improvement of a 50-hp polyphase induction motor. Other induction motors from 1 to over 200 hp have followed a similar trend.

2.5 EFFICIENCY DETERMINATION

Efficiency is defined as the ratio of the output power to the input power to the motor expressed in percent; thus,

$$\text{Percent efficiency} = \frac{W_{out} \times 100}{W_{in}}$$

TABLE 2.4b Full-Load Nominal Efficiencies of Three-Phase Four-Pole Energy-Efficient TEFC Motors

hp	Nominal efficiency range		Average nominal efficiency
	Min.	Max.	
1	77.0	85.5	82.5
2	82.5	86.5	84.2
3	82.5	89.5	87.8
5	85.5	90.2	88.4
7.5	87.5	91.0	90.3
10	89.5	91.7	90.6
15	91.0	92.5	92.0
20	91.9	93.0	92.6
25	92.3	94.1	93.1
30	92.6	94.1	93.4
40	93.1	94.5	93.8
50	93.2	95.0	94.0
60	93.6	95.0	94.4
75	93.8	95.4	94.7
100	94.1	95.4	94.9
125	94.2	95.8	95.2
150	94.2	96.2	95.4
200	95.2	96.2	95.7

^aBased on available published data.

It may also be expressed as

$$\text{Percent efficiency} = \frac{W_{out} \times 100}{W_{out} + W_{loss}}$$

where

W_{out} = output power, W

W_{in} = input power, W

W_{loss} = motor losses, W

The total motor losses include the following losses:

$$W_{loss} = W_s + W_r + W_c + W_f + W_{sl}$$

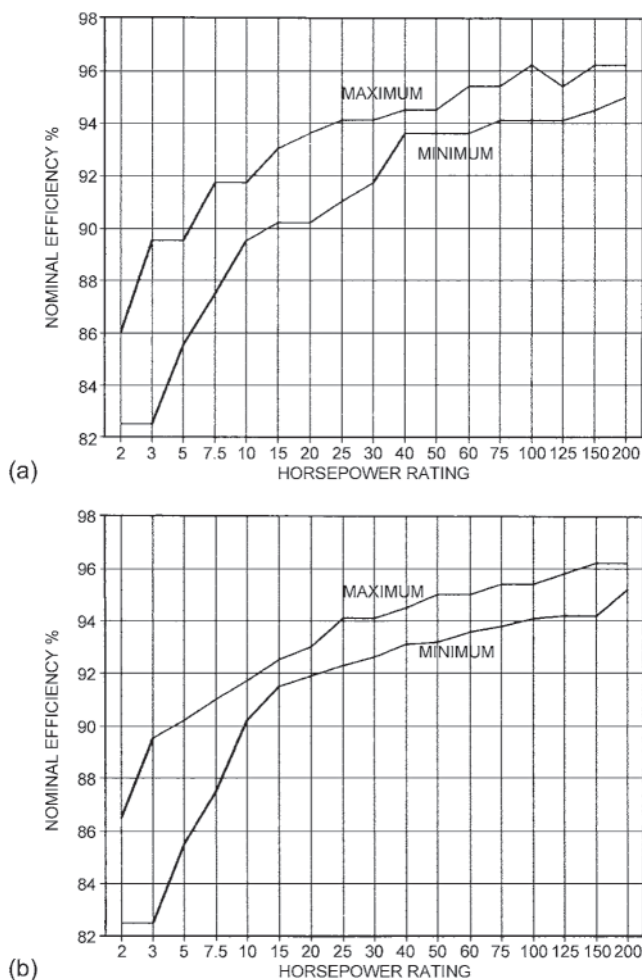


FIGURE 2.5 (a) Range of nominal efficiency for current industry energy-efficient open 1800-rpm induction motors. (b) Range of nominal efficiency for current industry energy-efficient TEFC 1800-rpm induction motors.

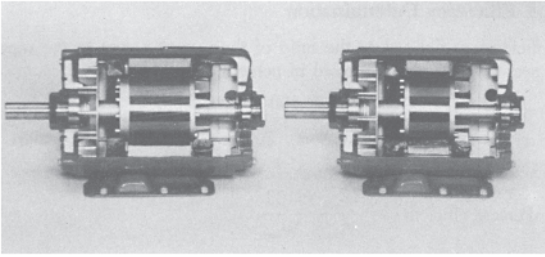


FIGURE 2.6 Comparisons of energy-efficient and standard motors. (Courtesy of MAGNETEK, St. Louis, MO.)

where

W_s = stator winding loss

W_r = rotor winding loss, slip loss

W_c = magnetic core loss

W_f = no-load friction and windage loss

W_{sl} = full-load stray load loss

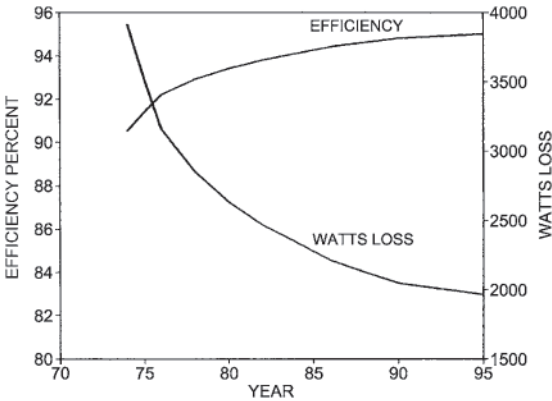


FIGURE 2.7 Loss reduction and efficiency improvement trend for 50-hp, 1800-rpm induction motor.

The accuracy of the efficiency determination depends on the test method used and the accuracy of the losses determined by the test method. There is no single standard method used throughout the industry. The most commonly referred to test methods are the following: IEEE Standard 112–1984 Standard Test Procedure for Polyphase Induction Motors and Generators; International Electrotechnical Commission (IEC) Publication 34-2, Methods of Determining Losses and Efficiency of Rotating Electrical Machinery from Tests; and Japanese Electrotechnical Commission (JEC) Standard 37 (1961), Standard for Induction Machines.

Each of these standards allows for more than one method of determining motor efficiency, and these can be grouped into two broad categories: direct measurement methods and segregated loss methods. In the direct measurement methods, both the input power and output power to the motor are measured directly. In the segregated loss methods, one or both are not measured directly. With direct measurement methods,

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power} \times 100}$$

With segregated loss methods,

$$\text{Efficiency} = \frac{\text{input power} - \text{losses}}{\text{input power}} \times 100$$

or

$$\text{Efficiency} = \frac{\text{output power}}{\text{output power} + \text{losses}} \times 100$$

2.5.1 IEEE Standard 112–1984

Methods A, B, and C are direct measurement methods:

Method A: Brake. In this method, a mechanical brake is used to load the motor, and the output power is dissipated in the mechanical brake. The brake's ability to dissipate this power limits this method

primarily to smaller sizes of induction motors (generally fractional horsepower).

Method B: Dynamometer. In this method, the energy from the motor is transferred to a rotating machine (dynamometer), which acts as a generator to dissipate the power into a load bank. The dynamometer is mounted on a load scale, a strain gauge, or a torque table. This is a very flexible and accurate test method for motors in the range 1–500 hp. However, to ensure accuracy, dynamometer corrections should be made as outlined in the test procedure. Method B includes a procedure for the stray load loss data smoothing by linear regression analysis. These smoothed values of stray load loss are used to calculate the final value of efficiency.

Method C: Duplicate Machines. This method uses two identical motors mechanically coupled together and electrically connected to two sources of power, the frequency of one being adjustable.* Readings are taken on both machines, and computations are made to calculate efficiency. This procedure includes a method of determining the stray load losses.

Methods E and F are segregated loss methods:

Method E: Input Measurements.[†] The motor output power is determined by subtracting the losses from the measure motor input power at different load points. For each load, the measured I^2R losses are adjusted for temperature and added to the no-load losses of friction, windage, and core. The stray load loss, which may be determined either directly, indirectly, or by the use of an agreed-on standardized value, is included in this total.

Method F: Equivalent Circuit Calculations. When load tests cannot be made, operating characteristics can be calculated from no-load and impedance data by means of an equivalent circuit. This equivalent circuit is shown in Fig. 2.8. Because of the nonlinear nature

* One machine is operated as a motor at rated voltage and frequency, and the other is driven as a generator at rated voltage per hertz but at a lower frequency to produce the desired load.

† In this method, it is necessary to connect the motor to a variable load. The input power is measured at the desired load points.

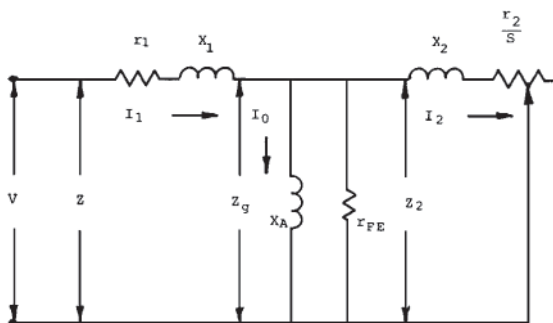


FIGURE 2.8 Polyphase induction motor per phase equivalent circuit. (From R. E. Osterlei, *Proceedings of the 7th National Conference on Power Transmission*, Gould Inc., St. Louis, MO, 1980.)

of these circuit parameters, they must be determined with great care to ensure accurate results. Procedures for determining these parameters are outlined in the standard as determined by a separate test. Accurate predictions of the motor characteristics depend on how closely r_2 represents the actual rotor resistance at low frequency.

2.5.2 IEC Publication 34-2

The same basic alternate methods as those outlined for IEEE 112 are also allowed for in IEC 34-2. However, a preference is expressed for the summation of losses method for the determination of motor efficiency. This is similar to IEEE 112 methods E and F except that the IEC method specifies stray load loss and temperature corrections differently. The IEC stray load losses are assumed to be 0.5% of rated input, whereas the IEEE standard states a preference for direct measurement of the stray load losses. The resistance temperature corrections in the IEC method are given as fixed values depending on insulation class, whereas the IEEE standard recommends use of the measured temperature rise for correcting resistance. These differences generally result in higher motor efficiency values by the IEC method.

2.5.3 JEC Standard 37

The JEC 37 standard also specifies the same basic methods as IEEE 112 with the exception of method C, duplicate machines. The preferred method for determining efficiency in this standard utilizes circle diagrams. This is a graphical solution of the T equivalent circuit of the induction motor. (This is similar to IEEE method F with the R_{fe} circuit branch.) As in the IEC standard, different methods are used to determine the circuit parameters and adjust the performance calculations. Principal among these is setting stray load loss equal to zero and using fixed values for resistance temperature corrections, which are a function of insulation class. These differences generally produce higher values for motor efficiency than the IEEE methods.

2.5.4 Comparison of Efficiencies Determined by Preferred Methods

To illustrate the variations in efficiency resulting from the use of the preferred methods, the full-load efficiency of several different polyphase motors was calculated by the preferred test methods given in the three standards. The results are shown in Table 2.5. As the values show, the efficiencies determined by the IEC and JEC methods are higher than the IEEE method. The major reason for this difference is the way in which stray load losses are accounted for. The IEEE method B stray load losses are included in the direct input and output measurements, whereas in the IEC method the stray load losses are

TABLE 2.5 Efficiency Determined by Preferred Methods

hp	JEC 37, circle diagram	IEC 34-2 loss summation	IEEE 112, method B
5	88.8	88.3	86.2
10	89.7	89.2	86.9
20	91.9	91.4	90.4
75	93.1	92.7	90.0

Source: R. E. Osterlei, *Proceedings of the 7th National Conference on Power Transmission*, Gould Inc., St. Louis, MO, 1980.

taken as 0.5% of the input, and in the JEC method they are set equal to zero. This comparison shows how important it is to know the method used to determine efficiency when comparing electric motor performance from different sources and countries.

2.5.5 Testing Variance

In addition to variance in efficiency due to test methods used, variances can also be caused by human error and test equipment accuracy. With dynamometer (IEEE 112, method B) testing, as with all test methods, there are several potential sources of inaccuracies: instrument accuracy, dynamometer accuracy, and instrument and dynamometer calibration. Therefore, to minimize these test errors, it is recommended that all the equipment and instruments be calibrated on a regular basis.

With proper calibration, dynamometer testing provides consistent and verifiable electric motor performance comparison. NEMA conducted a round-robin test of three different horsepower ratings (5, 25, and 100 hp) with a number of electric motor manufacturers. After a preliminary round of testing, each manufacturer was requested to test the motors in accordance with IEEE 112, method B, both with and without mathematical smoothing of the stray load loss. The results of these tests are summarized in Table 2.6.

TABLE 2.6 Variation in Test Data

hp rating	Variation in full-load efficiency			
	Without stray smoothing		With stray smoothing	
	Mean efficiency	Variation $\pm$ two std. deviations	Mean efficiency	Variation $\pm$ two std. deviations
5	86.3	2.0	87.1	0.7
25	89.6	1.3	89.5	0.8
100	92.7	1.3	91.9	0.9

Source: R. E. Osterlei, *Proceedings of the 7th National Conference on Power Transmission*, Gould Inc., St. Louis, MO, 1980.

Based on the test results, NEMA adopted a standard test procedure for polyphase motors rated 1–125 hp in accordance with IEEE Standard 112, method B, including mathematical smoothing of the stray load loss. It is recommended that this method of determining motor efficiency be used wherever possible.

2.6 MOTOR EFFICIENCY LABELING

Coincident with the NEMA test program, it was determined that a more consistent and meaningful method of expressing electric motor efficiency was necessary. The method should recognize that motors, like any other product, are subject to variations in material, manufacturing processes, and testing that cause variations in efficiency on a motor-to-motor basis for a given design.

No two identical units will perform in exactly the same way. Variance in the electrical steel used for laminations in the stator and rotor cores will cause variance in the magnetic core loss. Variance in the diameter and conductivity of the magnet wire used in the stator winding will change the stator winding resistance and hence the stator winding loss. Variances in the conductivity of aluminum and the quality of the rotor die casting will cause changes in the rotor power loss. Variances also occur in the manufacturing process. The quality of the heat treatment of the laminations for the stator and rotor cores can vary, causing a variance in the magnetic core loss. The winding equipment used to install the magnet wire in the stator can have tension that is too high, stretching the magnet wire and thus increasing the stator winding resistance and resulting in an increase in the stator winding loss I^2R . Similarly, other variances, such as dimensional variances of motor parts, will contribute to the variation in motor efficiency.

It is a statistical fact that a characteristic of a population of a product will generally be distributed according to a bell-shaped or gaussian distribution curve. The height of the curve at any point is proportional to the frequency of occurrences, as illustrated in [Fig. 2.9](#).

In the case of electric motors, the variation of losses for a population of motors of a given design is such that 97.7% of the motors will have an efficiency above the minimum efficiency defined

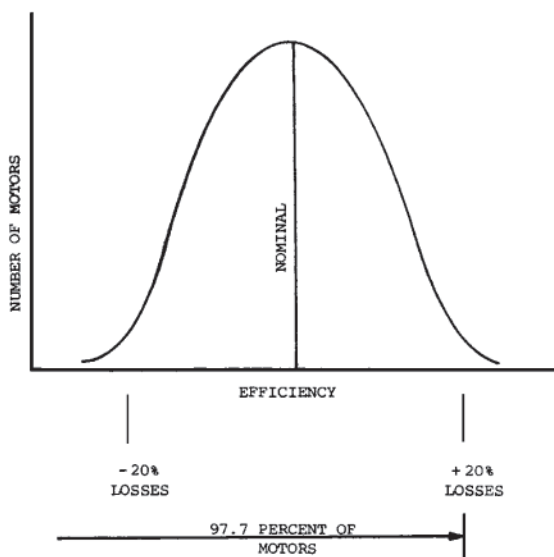


FIGURE 2.9 Normal frequency distribution.

by a variation of motor losses of $\pm 20\%$ of the losses at the nominal or average efficiency. Figure 2.10 illustrates the efficiency distribution for a specific value of nominal efficiency of 91%.

It is possible as motor manufacturers gain experience with this procedure that variations in losses will be lower than $\pm 20\%$. In this event, the spread between nominal efficiency and minimum efficiency can be reduced.

Consequently, NEMA adopted a standard publication, MG1-12.54.2, recommending that polyphase induction motors be labeled with a NEMA nominal efficiency (or NEMA NOM EFF) when tested in accordance with IEEE Standard 112, dynamometer method, with stray loss smoothing. In addition, a minimum efficiency value was developed for each nominal efficiency value. Table 2.7 is a copy of the NEMA efficiency Table 12-6a. It is recommended that this method of labeling efficiency and testing be specified whenever possible.

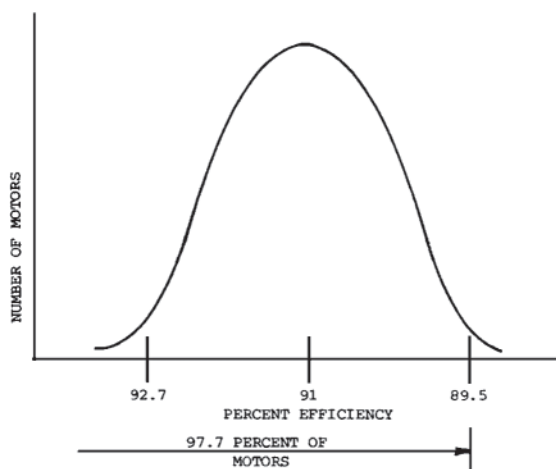


FIGURE 2.10 Normal efficiency distribution.

In instances in which guaranteed efficiencies are required, it is recommended that the preceding test method or an appropriate test method including the method of loss determination and the losses to be included in the efficiency determination be specified.

2.7 NEMA ENERGY-EFFICIENT MOTOR STANDARDS

In 1990, based on the experience gained by the electric motor manufacturers in producing energy-efficient polyphase induction motors and interest by industry, NEMA adopted a suggested standard for future design defining energy-efficient motors and setting efficiency levels for energy-efficient motors. These standards are as follows:*

MG1-2.43 Energy Efficient Polyphase Squirrel-cage Induction Motor. An energy efficient polyphase squirrel-cage induction

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TABLE 2.7 NEMA Nominal Efficiencies NEMA Table 12-6A

Nominal efficiency	Minimum efficiency	Nominal efficiency	Minimum efficiency
98.0	97.6	87.5	85.5
97.8	97.4	86.5	84.0
87.6	97.1	85.5	82.5
97.4	96.8	84.0	81.5
97.1	96.5	82.5	80.0
96.8	96.2	91.5	78.5
96.5	95.8	80.0	77.0
96.2	95.4	78.5	75.5
95.8	95.0	77.0	74.0
95.4	94.5	75.5	72.0
95.0	94.1	74.0	70.0
94.5	83.6	72.0	68.0
94.1	93.0	70.0	66.0
93.6	92.4	68.0	64.0
93.0	91.7	66.0	62.0
92.4	91.0	64.0	59.5
91.7	90.2	62.0	57.5
91.0	89.5	59.5	55.0
90.2	88.5	57.5	52.5
89.5	87.5	55.0	50.5
88.5	86.5	52.5	48.0

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motor is one having an efficiency in accordance with MG1-12.55A. Suggested Standard for Future Design.

MG1-12.55A Efficiency Levels of Energy Efficient Polyphase Squirrel-cage Induction Motors. The nominal full-load efficiency determined in accordance with MG1-12.54.1 and identified on the nameplate in accordance with MG1-12.54.2 shall equal or exceed the values listed in Table

TABLE 2.8 NEMA Table 12-6c Full-Load Nominal Efficiencies and Associated Minimum Efficiencies for Polyphase Induction Motors

hp	2-Pole		4-Pole		6-Pole		8-Pole	
	Nom.	Min.	Nom.	Min.	Nom.	Min.	Nom.	Min.
1.0	—	—	82.5	81.5	80.0	78.5	74.0	72.0
1.5	82.5	81.5	84.0	82.5	84.0	82.5	75.5	74.0
2.0	84.0	82.5	84.0	82.5	85.5	84.0	85.5	84.0
3.0	84.0	82.5	86.5	85.5	86.5	85.5	86.5	85.5
5.0	85.5	84.0	87.5	86.5	87.5	86.5	87.5	86.5
7.5	87.5	86.5	88.5	87.5	88.5	87.5	88.5	87.5
10.0	88.5	87.5	89.5	88.5	90.2	89.5	89.5	88.5
15.0	89.5	88.5	91.0	90.2	90.2	89.5	89.5	88.5
20.0	90.2	89.5	91.0	90.2	91.0	90.2	90.2	89.5
25.0	91.0	90.2	91.7	91.0	91.7	91.0	90.2	89.5
30.0	91.0	90.2	92.4	91.7	92.4	91.7	91.0	90.2
40.0	91.7	91.0	93.0	92.4	93.0	92.4	91.0	90.2
50.0	92.4	91.7	93.0	92.4	93.0	92.4	91.7	91.0
60.0	93.0	92.4	93.6	93.0	93.6	93.0	92.4	91.7
75.0	93.0	92.4	94.1	93.6	93.6	93.0	93.6	93.0
100.0	93.0	92.4	94.1	93.6	94.1	93.6	93.6	93.0
125.0	93.6	93.0	94.5	94.1	94.1	93.6	93.6	93.0
150.0	93.6	93.0	95.0	94.5	94.5	94.1	93.6	93.0
200.0	94.5	94.1	95.0	94.5	94.5	94.1	93.6	93.0

Enclosed Motors

1.0	75.5	74.0	82.5	81.5	80.0	78.5	74.0	72.0
1.5	82.5	81.5	84.0	82.5	85.5	84.0	77.0	75.5
2.0	84.0	82.5	84.0	82.5	86.5	85.5	82.5	81.5
3.0	85.5	84.0	87.5	86.5	87.5	86.5	84.0	82.5
5.0	87.5	86.5	87.5	86.5	87.5	86.5	85.5	84.0
7.5	88.5	87.5	89.5	88.5	89.5	88.5	85.5	84.0
10.0	89.5	88.5	89.5	88.5	89.5	88.5	88.5	87.5
15.0	90.2	89.5	91.0	90.2	90.2	89.5	88.5	87.5
20.0	90.2	89.5	91.0	90.2	90.2	89.5	89.5	88.5
25.0	91.0	90.2	92.4	91.7	91.7	91.0	89.5	88.5
30.0	91.0	90.2	92.4	91.7	91.7	91.0	91.0	90.2
40.0	91.7	91.0	93.0	92.4	93.0	92.4	91.0	90.2
50.0	92.4	91.7	93.0	92.4	93.0	92.4	91.7	91.0

TABLE 2.8 Continued

hp	2-Pole		4-Pole		6-Pole		8-Pole	
	Nom.	Min.	Nom.	Min.	Nom.	Min.	Nom.	Min.
60.0	93.0	92.4	93.6	93.0	93.6	93.0	91.7	91.0
75.0	93.0	92.4	94.1	93.6	93.6	93.0	93.0	92.4
100.0	93.6	93.0	94.5	94.1	94.1	93.6	93.0	92.4
125.0	94.5	94.1	94.5	94.1	94.1	93.6	93.6	93.0
150.0	94.5	94.1	95.0	94.5	95.0	94.5	93.6	93.0
200.0	95.0	94.5	95.0	94.5	95.0	94.5	94.1	93.6

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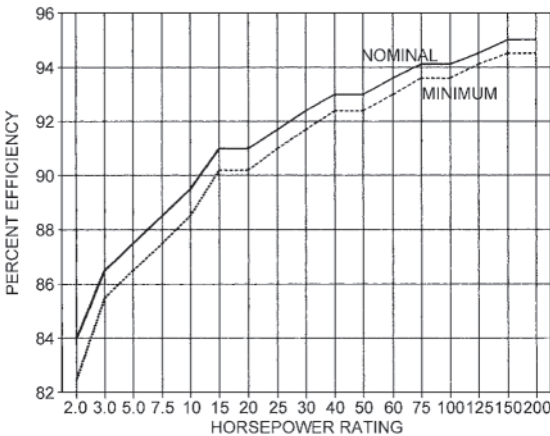


FIGURE 2.11 NEMA energy-efficiency standards for four-pole open induction motors from data in Table 2.8. (Courtesy National Electrical Manufacturers Association, Washington, DC.)

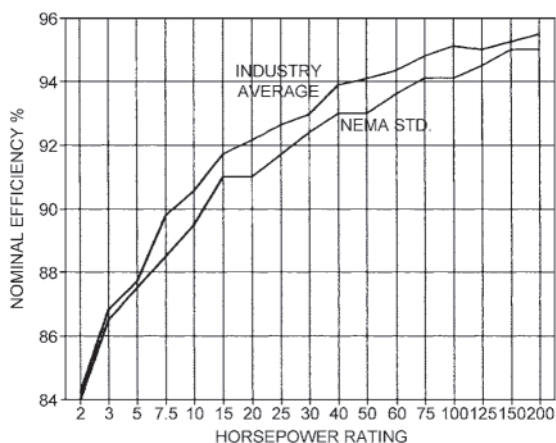


FIGURE 2.12 Comparison of NEMA nominal efficiency and available industry average efficiency for 1800-rpm open energy-efficient motors.

12-6c for the motor to be classified as “energy-efficient.”
Suggested Standard for Future Design.

As mentioned earlier, the variation in the nominal efficiency of energy-efficient induction motors has been smaller than for standard induction motors. In addition, the electric motor manufacturers have experienced less efficiency variation in their product. This is reflected in the NEMA standard for energy-efficient motors, in that the variation in the allowable losses has been reduced to $\pm 10\%$, which means a higher minimum efficiency for a given nominal efficiency. Table 2.8 is a copy of the NEMA Table 12-6C with the higher full-load nominal and minimum efficiency standards for energy-efficient motors, both open and TEFC, at various speeds. Figure 2.11 shows the relationship between the NEMA nominal efficiency and the minimum efficiency for energy-efficient four-pole open motors. Figure 2.12 is a comparison of the NEMA nominal efficiencies and the average of the available industry energy-efficient four-pole open motors. This indicates that available energy-efficient motors have efficiencies slightly higher than the NEMA standard.